IMPACTS AND TECTONISM IN EARTH AND MOON HISTORY OF THE PAST 3800 MILLION YEARS

RICHARD B. STOTHERS

NASA, Goddard Space Flight Center, Institute for Space Studies, New York, U.S.A.

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Abstract. The Moon's surface, unlike the Earth's, displays a comparatively clear record of its past bombardment history for the last 3800 Myr, the time since active lunar tectonism under the massive pre-mare bombardment ended. From Baldwin's tabulation of estimated ages for a representative sample of large lunar craters younger than 3800 Ma, six major cratering episodes can be discerned. These six bombardment episodes, which must have affected the Earth too, appear to match in time the six major episodes of orogenic tectonism on Earth, despite typical resolution errors of ± 100 Myr and the great uncertainties of the two chronologies. Since more highly resolved events during the Cenozoic and Mesozoic Eras suggest the same correlation, it is possible that large impacts have influenced plate tectonics and other aspects of geologic history, perhaps by triggering flood basalt eruptions.

1. Introduction

To understand the Earth's cratering history, it is useful to turn to the well-preserved surface of the Moon. Since few but the largest known impact structures on the Earth predate the Mesozoic, owing to tectonism and the continual erosion and burial that affect even the stable continental cratons, clues to earlier terrestrial eras may be derived from dated impact craters on a neighboring 'dead' body that has been subjected to essentially the same bombardment history. The question of the possible effect of large impacts on the Earth's tectonic processes can be studied in a rough quantitative fashion, because the coarse records of large lunar impacts and of major periods of terrestrial orogeny are probably adequately known back to the termination of the massive pre-mare bombardment.

Physical and statistical evidence suggests plausibly, though by no means conclusively, that large impacts on the Earth could have triggered the known continental flood basalts of Cenozoic and Mesozoic times by excavating and decompressing hot-spot swells (Stothers and Rampino, 1990). The expected final crater diameter for a sufficiently large impact is $D > 100$ km, on the average (but the lower limit on D is smaller under oceans and larger in continental interiors). In many cases, flood basalt outbreaks are known to have been closely associated with continental rifting and tectonism, or at least an intensification of tectonism (e.g., Morgan, 1981; White and McKenzie, 1989; Hooper, 1990; Hill, 1991). Although mantle convection, tectonic plate motions, and continental collisions and dispersals are doubtless the main driving factors for tectonism, large impacts could have modulated these processes, via the triggering of flood basalt eruptions, and may therefore have affected both the timing and intensity of tectonism.

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The present investigation of large pre-Mesozoic impacts and of contemporaneous orogenic tectonism is forced to examine the question of a correlation somewhat obliquely, using the lunar impact record, and therefore is necessarily offered in a rather speculative spirit. It is nevertheless worthwhile just to point out the interesting discovered correlation, although only future work will be able to verify or reject its physical significance.

2. Orogenic Episodes

On the Earth, the dated record of rock formation goes back to the terminal Hadean, 3800 Ma, with only a few older rocks being known. If ordinary terrestrial rock-forming processes have been modified by the impacts of large extraterrestrial bodies, the available petrologic record might show the effect.

The coincidence in time between the bulk of the oldest existing terrestrial rocks and the rapid termination of the massive pre-mare bombardment on the Moon is one indication of such a physical connection (Green, 1972). Since such enormous impacts appear not to have been afterward repeated, the subsequent history of the Earth's crust is at least known in very general outline (Condie, 1984; Jacobsen, 1988).

Six great post-Hadean episodes of rock formation have now been recognized in Earth history by a number of authors. These episodes are listed in Table I, where three are designated by the names of their Canadian Shield prototypes following Fitch *et al.* (1974). The six episodes were global (or at least broadly regional) in character, being now recognized on all or most of the major stable cratons. They consisted of long periods of intermittent igneous, metamorphic, and orogenic activity, and have been identified by the authors cited in Table I from peaks in the frequency distributions of radiometric and isotopic ages of sampled rock minerals and metallic ores. Sedimentary rock formations (Garrels and Mackenzie, 1969; McCulloch and Wasserburg, 1978) and banded iron formations (Eichler, 1976) show broadly the same temporal variations, although they probably lag in time the formations of the igneous rocks. The banded iron formations are also useful because they substantiate Dearnley's (1965, 1966) Middle Archean orogenic episode. Although the older compilations in Table I are now often disregarded, they do usefully show the near constancy of both the identifications and the assigned dates of the six major episodes as more and better age data have become available. The orogenic episodes appear to have occupied, either wholly or partly, the following time intervals: 3800–3500 Ma (Early Archean), 3150–3000 Ma (Middle Archean), 2850–2500 Ma (Superior), 1950–1600 Ma (Churchill), 1200–900 Ma (Grenville), and 600–0 Ma (Phanerozoic). The two earliest episodes, however, are still quite uncertain, and it is possible that the unusually long Phanerozoic episode actually consisted of two shorter episodes, occupying the approximate intervals 600–250 Ma and 180–0 Ma (Gastil, 1960; Dearnley, 1965, 1966; Garrels and Mackenzie, 1969; Meyer, 1988). Formal resolution errors of the dates for the

TABLE I

Ages (Ma) of major terrestrial orogenic periods

Early Archean	Middle Archean	Superior	Churchill	Grenville	Phanerozoic	Source
–	–	2650 ± 150	1800 ± 90	1030 ± 50	550 ± 10	Voitkevich (1958)
–	–	2710 to 2490	1860 to 1650	1100 to 930	620 to 0	Gastil (1960)
–	(3200 ± 300)	(2600 ± 200)	(1900 ± 100)	–	–	Vinogradov and Tugarinov (1961)
–	–	2800 ± 100	1800 ± 100	1100 ± 100	–	Sutton (1963)
–	–	(2490 ± 60)	(1735 ± 60)	(945 ± 60)	–	Stockwell (1964, 1968)
–	3100 ± 50	2750 ± 50	1950 ± 50	1075 ± 50	650 ± 50	Dearnley (1965, 1966)
4100 to 3500	–	2950 to 2400	1950 to 1550	1150 to 850	550 to 250	Fitch *et al.* (1974)
3800 to 3500	–	2900 to 2600	1900 to 1600	1200 to 900	600 to 0	Moorbath (1977)
–	–	(2600 ± 30)	–	(1000 ± 10)	–	McCulloch and Wasserburg (1978)
–	–	2900 to 2400	1950 to 1600	1200 to 900	600 to 0	Meyer (1988)
–	–	–	2000 to 1600	1300 to 900	600 to 0	Hoffman (1988)
–	–	2800 to 2600	1900 to 1700	–	–	Condie (1989)

A single age listed with an estimate of uncertainty refers to the start date of an orogenic period unless the age is placed in parentheses, in which case it refers to the mean date.

five Precambrian episodes are ±50 Myr. About half of the whole 3800–Myr interval of time was relatively anorogenic.

It should be pointed out that an orogenic episode (or period) as defined here and elsewhere is known to have consisted of many individual events, each relatively sharp, short-lived (millions to tens of millions of years), and local. Evidence for this is very strong in the Phanerozoic and exists also in parts of the Precambrian record. The individual events are very accurately dated in some cases, but it is not yet known how rapidly an episode as a whole developed and then decayed. This accounts for the sizable resolution errors of the episodes' assigned dates. Lulls between episodes were not absolute, and so whatever mechanism caused the episodicity must have operated with only mild, temporary enhancements above the background intensity.

In the framework of plate tectonics and continental drift theory, these orogenic episodes are believed to be closely related to the formation and breakup of supercontinents. The possible role of impacts of large extraterrestrial bodies in this process, however, has not yet been studied, except, in part, for the Late Phanerozoic. To proceed further, the chronology of lunar impacts will be examined for possible episodicity that might be contemporaneous with orogenic episodes on the Earth.

3. Lunar Craters

On the Moon, small number statistics pose a potential problem when dealing with the largest impact craters (Wilhelms, 1987). For example, the 10 largest craters of the last 3200 Myr all formed on the Moon's near side (whereas no such dichotomy exists for the 100 largest craters), and no very large craters with diameters $D > 140$ km (corresponding to $D > 100$ km on the Earth) formed on either side of the Moon during the last 1100 Myr, although two might have been expected by extrapolating from the Earth's Cenozoic and Mesozoic crater statistics (Stothers and Rampino, 1990). To circumvent this statistical problem of small numbers, the very rare largest inner Solar System impactors, which have been conjecturally associated with flood basalt volcanism on the Earth, will be assumed to have followed in time the same frequency distribution as the more numerous, smaller lunar craters with $D \geqslant 8$ km, at least for post-Orientale times, the last 3800 Myr. The validity of this assumption is supported by Figure 1, showing the cumulative crater number versus size distribution, which closely resembles the $N \propto D^{-1.8}$ distribution found for large impact craters on the Earth (Grieve, 1987).

Baldwin (1985) has estimated very roughly the ages of a large sample of lunar craters with $D \geqslant 8$ km by combining counts of smaller superposed lunar craters (as a function of crater diameter) with radiometric ages of young, equivalent terrestrial impact craters and of returned lunar rock samples. He used seven calibration ages: 0 and 300 Ma, derived from equivalent terrestrial impact craters; 3200 Ma, from Apollo 12 sample returns; 3850 Ma, from Apollo 15 sample returns;

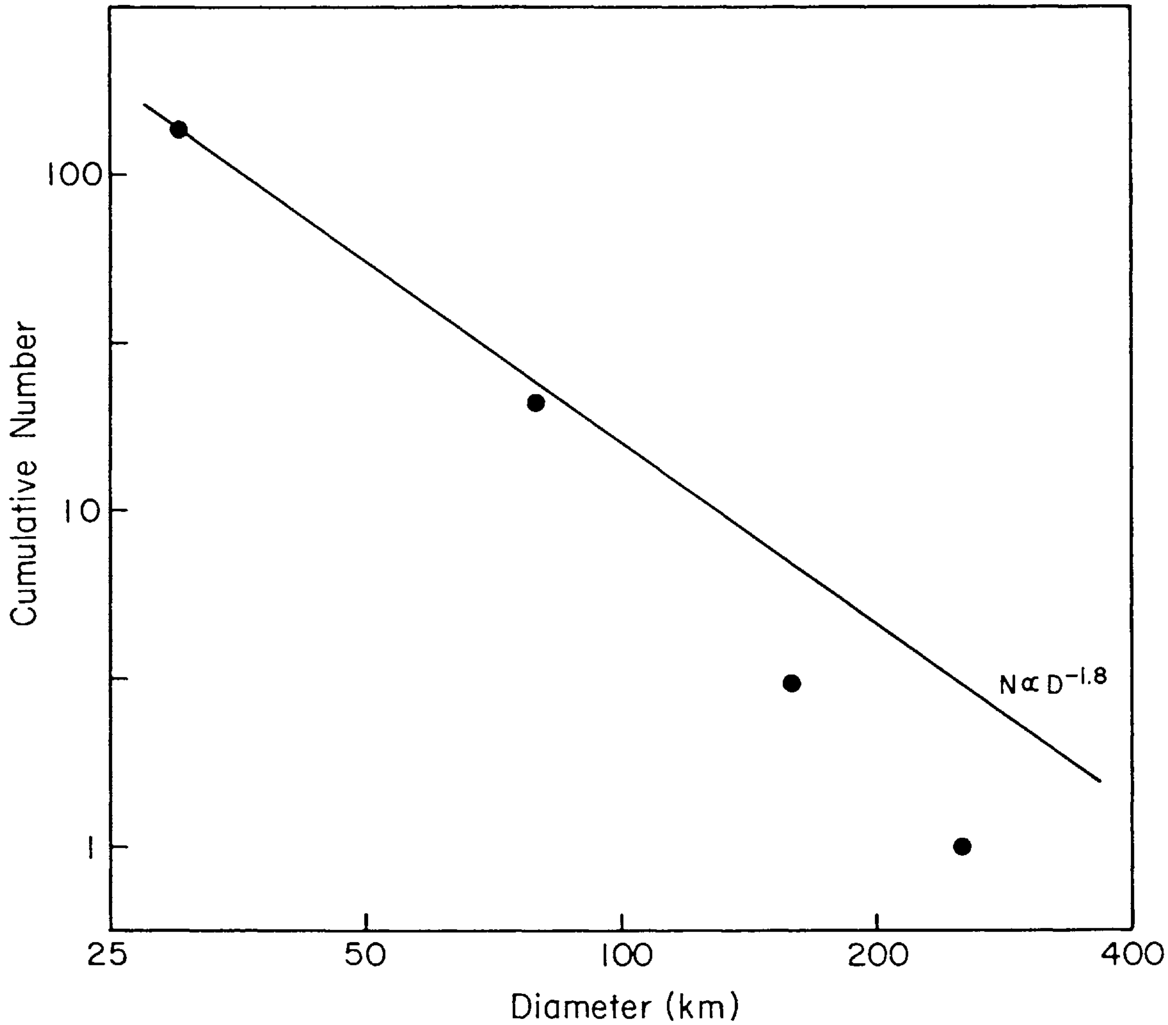

Fig. 1. Cumulative number of post-Orientale impact craters on the near side of the Moon as a function of their diameters (data from Wilhelms).

and 3500, 3800, and 3820 Ma, from several large lunar surface units that Wilhelms (1987) had dated by interpolation using crater diameters. Two partial checks on Baldwin's (1985) results were provided by weakly determined radiometric ages of two lunar craters, Tycho (109 ± 4 Ma) and Copernicus (800–850 Ma), for which his interpolation method yielded 138 ± 22 Ma and 834 ± 65 Ma, respectively. Furthermore, he also found the estimated present rates of formation of lunar and terrestrial impact craters to be consistent with each other (Baldwin, 1987). Owing to their statistical character, however, the deduced ages of lunar craters are not very accurate, but Baldwin argued that they should be adequate for studies of long-term variations in the cratering rate. He thereby showed that, after the massive pre-mare bombardment, the cratering rate slowly increased on the average, doubling between 3000 Ma and the present, although Wilhelms (1987), in a much less detailed analysis, found a slight decrease rather than an increase.

Several long-term oscillations in the cratering rate were found by Baldwin (1985) to have accompanied this secular change. To investigate the authenticity and

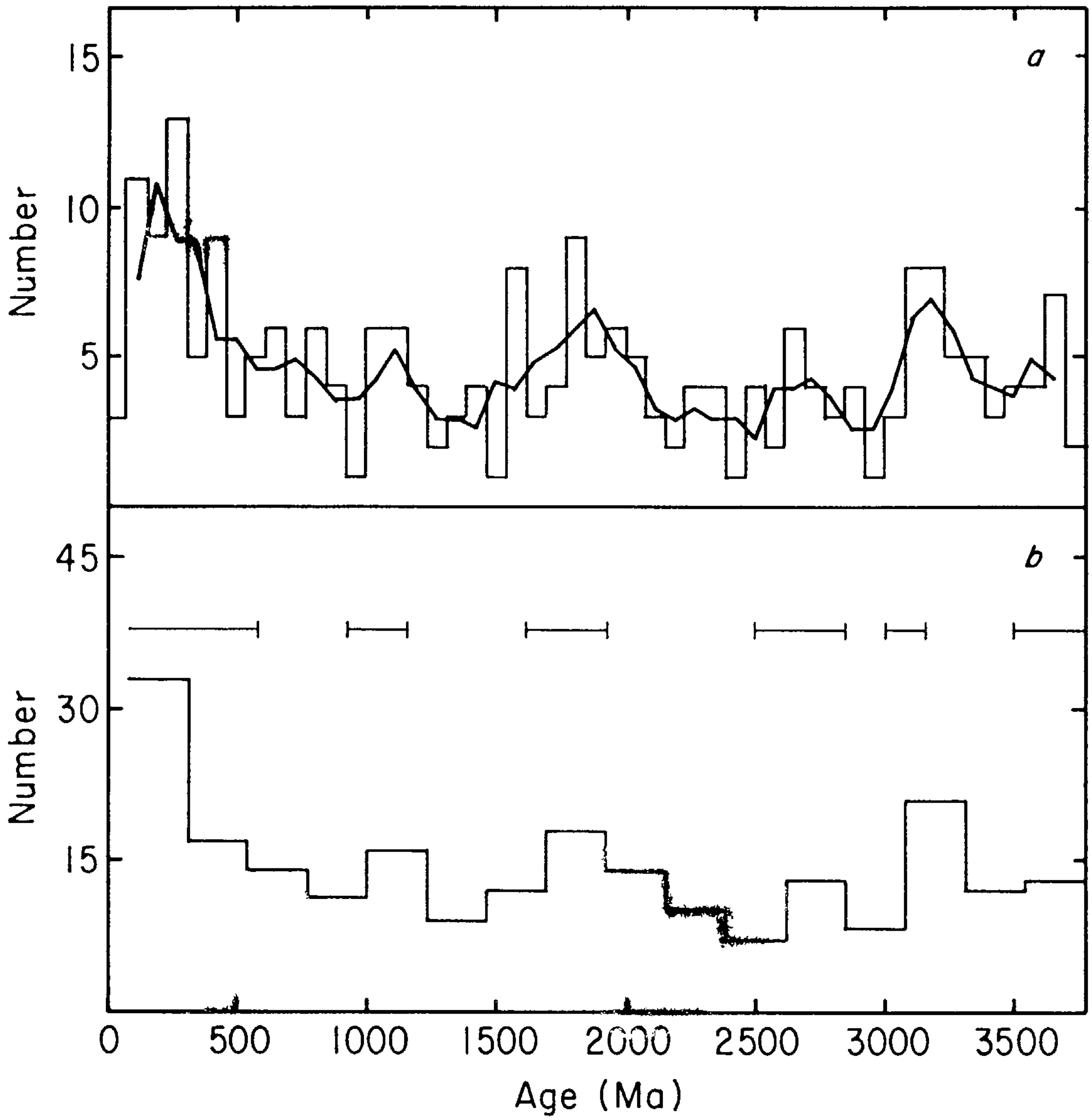

Fig. 2. Number of post-Orientale impact craters with $D \geqslant 8$ km as function of their estimated ages, from Baldwin's sample of dated lunar craters. A three-bin running mean is represented by the heavy line. Horizontal bars indicate the age spreads of the six major periods of orogenic tectonism on the Earth.

statistical properties of these oscillations, a more careful consideration of how the time series was constructed is necessary. Baldwin adopted a set of six linear relations tying the ages of the craters with $D \geqslant 8$ km (which were placed in six successive age intervals defined by the seven calibration dates) to the extrapolated 1 km intercepts of the cumulative counted crater numbers (the intercepts are defined as the cumulative numbers of superposed craters with $D \geqslant 1$ km over a normalized surface area of 1 km^2). In this process, it was assumed that both the size-frequency distribution and the integrated flux of small impactors were uniform in time. If this dual assumption is invalid, as it probably was during times of enhancement of the flux of larger impactors and possibly at other times as well, it would only serve to smear out the distribution of inferred ages and hence to artificially damp the true oscillations in the derived cratering rate and to misplace the peaks somewhat in time. If, therefore, any oscillations are detected under this assumption, they may possibly be indicative of significantly stronger, real oscillations rather than of purely stochastic $n^{1/2}$ noise arising from accidental errors in the derived ages. This can be partially checked both by the use of data culling and by the use of correlative time series, as shown below.

By rounding off all the numerical values of the 1 km intercepts, however, Baldwin (1985) inadvertently introduced a periodic regularity into the interpolated crater ages. Because of this built-in bias, a histogram of Baldwin's lunar crater ages is replotted here in Figure 1a by using bins of width 76.3 Myr, the artificial periodicity of the 3200 to 300 Ma age interval. Bin widths for ages older than 3200 Ma and younger than 300 Ma are chosen for consistency to be essentially the same value, 75 Myr; the oldest ages are cut off at 3800 Ma, the end of the massive pre-mare bombardment. The total number of ages shown is 231. In view of the average 1σ analytical age error of ± 200 Myr for an individual crater (the true error of course could be larger), the plotted histogram is also shown filtered with a three-bin running mean. In Figure 1b, a histogram with a tripled bin size of 229 Myr is plotted for comparison.

Filtering in either way reveals six major episodes of apparently stepped-up rates of cratering, three of which are somewhat more prominent than the others. The oldest of the six episodes probably represents the tail end of the massive pre-mare bombardment. Are these episodes real? If only Baldwin's 15 largest craters with $D \geqslant 40$ km are used, the same pattern of cratering emerges. Also consistent with this pattern is the near coincidence in time of the two largest known pre-Mesozoic impact structures on the Earth, Sudbury (1850 ± 150 Ma) and Vredefort (1970 ± 100 Ma) (both with $D = 140$ km) (Grieve, 1987), and of four prominent iridium-enriched Archean spherule beds, believed to have been laid down by large impacts at roughly 3200 to 3500 Ma (Lowe *et al.*, 1989). In addition, several clusters of cratering events are known for the Late Phanerozoic (e.g., Stothers and Rampino, 1990).

Resolution errors of the dates of the six major cratering episodes can be roughly estimated as follows. If there are n ages in a bin and the typical standard error of an individual age in that bin is σ, then the standard error of the bin's mean age is approximately $\sigma/n^{1/2}$. The bins of width 229 Myr in Figure 1b have an average $n = 14$ and so $\sigma/n^{1/2} \sim 50$ Myr. Since the mean ages of contiguous bins are separated by about twice the bins' typical standard age error compounded in both directions, the analytical errors in the locations of the cratering pulses in Figure 1b may be taken to be roughly ± 100 Myr. However, the true errors could be larger.

4. Discussion

The apparent timings of the most important long-term bombardment episodes of the last 3800 Myr in the inner Solar System are found to coincide, up to the limit of the coarse present resolution, with the estimated timings of the six major periods of orogenic tectonism on the Earth. By noting the a priori unlikelihood of an accidental equality between the total numbers of orogenic and impact episodes and by assuming that the probability of an accidental overlap between each matched pair of orogenic and impact episodes is roughly 1/2, the chance that all six coincidences are accidental is estimated to be of the order of magnitude of $(1/2)^6 = 0.016$. A more sophisticated analysis would be unwarranted by the present crude data. The match must therefore be regarded as suggestive, but certainly not proven until Baldwin's lunar chronology is independently confirmed.

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